Progress Report

Grant #731009
Ultra-Efficient Generators & Diesel Electric Propulsion
Genesis Machining & Fabrication
Reporting Dates: 6/2013-9/2013

Deliverables Submitted:

No deliverables are due at this time. However, we are submitting the initial results from our proof-of-concept inverting genset.

Budget:

We are invoicing for a total of $7,769.55 for materials purchased and $4,375.00 in labor for this quarter. We are also requesting $4,375.00 in advanced labor, and $2,500.00 in advance for legal fees related to intellectual property protection (see advance narrative and below). Of the materials advance given last quarter $642.22 remains to be spent on backup-battery cells for the EV testbed. We are submitting documentation for $12,100.00 in match for rent, utilities, and labor.

Schedule Status:

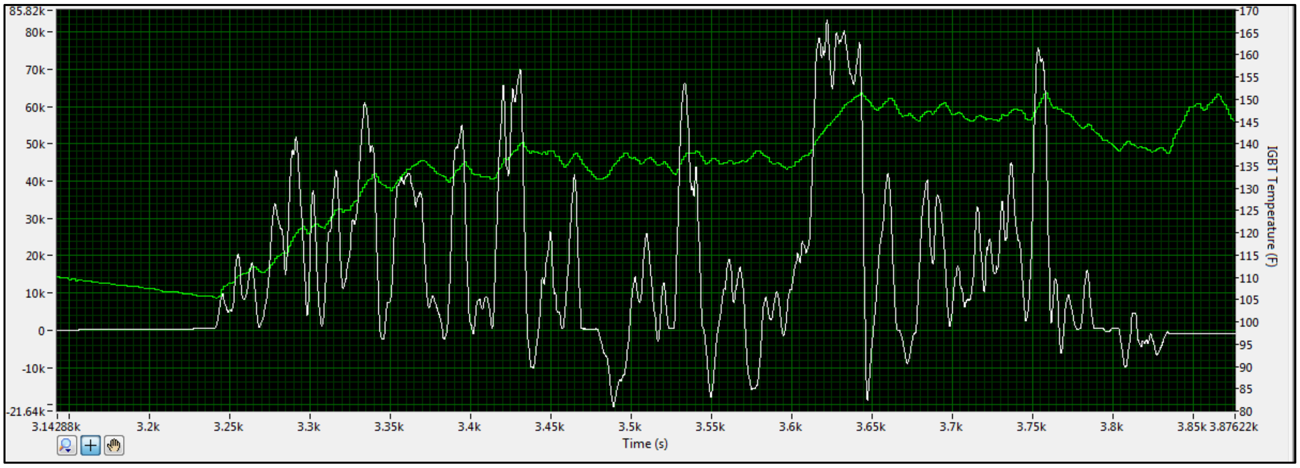
We are still behind in delivering motor efficiency data. We tried to accomplish this during the quarter but the lead time on the torque sensor was too long, so we will do it during the 10/13-12/13 quarter.

Work Progress:

1. Inverter reliability and high load testing

   Our EV testbed was used to gather inverter reliability and performance data during this quarter. Since the last quarter we have replaced a faulty set of IGBT's and identified electrostatic discharge during the IGBT driver installation process as the point of failure. With a new set of IGBT's and new set of AgileSwitch's latest driver modules, we have logged hundreds of operational hours, and around 1000 miles at full pack voltage (~400V) without logging a single IGBT fault. In addition to long periods of on-time, we have also power tested up to 83 kW. We were limited from higher power levels because the vehicle speed was very high and we have not yet had time to install our balanced racing clutch. Once this is done, we can run at higher RPM's in lower gears and pull loads to bring the inverter up to yet higher power levels. Thus far, performance data is very good and we have successfully run 83 kW through the inverter. We experienced no excessive heating in either the motor or the inverter at this power level.

   The graph below shows seven minutes of data that was recorded driving the EV aggressively on hilly, winding roads. The white line is power out of the inverter, and the green line is IGBT die temperature. Areas with negative power represent regen braking.



We did not focus on efficiency measurements, but simply on functionality at higher power levels. Performance was excellent in that the car was cruising at 65 mph up a steep hill for the peak output section of the graph and no adverse IGBT heating occurred. During the next quarter we will develop real-time efficiency measurement code on the FPGA for the inverter and the motor.

2. Torque and Fuel Meter Procurement

We have not yet measured our PDM efficiency because of the lead-time for the torque meter. A meter was selected and purchased through ACEP, but the company had a 1-month lead time. Once this device arrives, we will be able to map the efficiency of our motor.

In addition to the torque meter, a precision fuel meter was also purchased in order to map the efficiency of our 15 kW proof-of-concept genset. Even though we do not yet have the meter, we have preliminary results from our genset which we will describe below.

3. EV Regen

We have successfully implemented regen braking in our electric vehicle thus demonstrating the use of the PDM winding configuration as a generator.

4. 15kW Load-Matching Genset

A. Setup

We began with a 12.5 kW genset consisting of a three cylinder, naturally aspirated, mechanically injected Isuzu diesel engine and a traditional self-exciting, wound-rotor alternator shown in fig.1.

Figure 1 - Genset prior to modification

The engine was completely rebuilt and the generator head was removed and replaced with a used, unmodified 15hp induction motor. A rubber coupling was used to connect the engine to the motor. Additionally, the water-to-water heat exchanger was replaced with a radiator and fan. The modified genset is shown in fig. 2.

Figure 2 - Modified Genset

Next, a servo was connected to the throttle input via a pushrod, and a gear-tooth sensor was installed next to the ring-gear so that the engine RPM could be precisely controlled via computer, see fig.3.

Figure 3 - Servo (left) and gear-tooth sensor (right)

Finally, the fuel return line was looped back to the input of the injection pump and a simple fuel measurement system was built. This engine, unlike many larger diesels, has a very slow return rate used for injector lubrication only, and had no problems operating in this mode. The fuel measurement system allows fuel volume to be measured over a given time interval via a sight-glass – it does not allow real-time metering, see fig.4. We have ordered an appropriate real-time meter via ACEP and should have it soon.

Figure 4 - Fuel measurement system with sight-glass

The induction motor was wired into one power layer of the UMIC (inverter) and a load panel and resistive loads were wired into the other power-layer of the UMIC. The load bank was built by installing four, 4500 W heating elements into a 55 gal. drum filled with water.

Figure 5 - Genset, fuel meter, load center, and load-bank (inverter not shown)

B. Procedure

An algorithm was developed to maintain constant RPM. Feedback from the gear-tooth sensor was used to control the angle of the throttle servo. This was implemented as a PID loop on the inverter's real-time microcontroller.

Another algorithm was designed on inverter's FPGA to maintain a constant voltage on the inverter DC-link. This was done by implementing an 80kHz PID loop which modulated the field-current of the induction motor. It should be noted that the inverter-fed induction generator system is inherently unstable and can have a run-away voltage if not tightly controlled. A FPGA over-voltage safety was also programmed. Along with the PID control loop, an FPGA based loop was written to fix the slip of the generator head to data from the gear-tooth sensor. For all of these tests the slip was set to -4 Hz. In other words, the generator stator field was always rotating 4 Hz slower than the rotor.

A) <u>Fixed RPM fuel efficiency test</u>

The DC link voltage was set to 300V, and the engine RPM was set to 1800 rpm. The output to the resistive load-bank was set to a fixed 60 Hz and the duty cycle was varied to produce different power outputs. At each output level, the time it took for 1' of fuel to be consumed from the sight glass was measured. Power was calculated by measuring current to the load and using the formula $P=I^2R$. Ideally, we would also do real-time voltage measurement and obtain real-time power, but did not in this case.

B) <u>Variable RPM fuel efficiency test</u>

For this test the DC link voltage was again set to 300V. The power to the load was set as closely as possible to the settings achieved for the fixed RPM test. Then, the RPM setting was lowered until the engine "sounded" sufficiently loaded. Without actually mapping the entire operating space of the system, it is impossible to know which RPM is the most efficient for a given load. For this experiment, we simply guessed based on the "feel" of the engine. Once an RPM had been chosen at each power level, the time it took for 1' of fuel to be consumed from the sight glass was measured.

C. Results

The raw data for both tests is shown below:

1800 RPM Power (W)	Seconds to burn 1' of fuel in sight	Variable RPM Power (W)	Seconds to burn 1' of fuel in sight
0	90.0	0	176.5
225	84.6	216	171.0
865	68.9	839	134.0
1965	54.6	1971	93.4
3415	44.3	3454	64.5
5943	33.4	5233	45.0
7743	26.9	7794	30.8
10773	24.1	10486	24.4

From this data, fuel consumption was calculated in gr/kWh and plotted against power delivered to the load, see fig. 6 below.

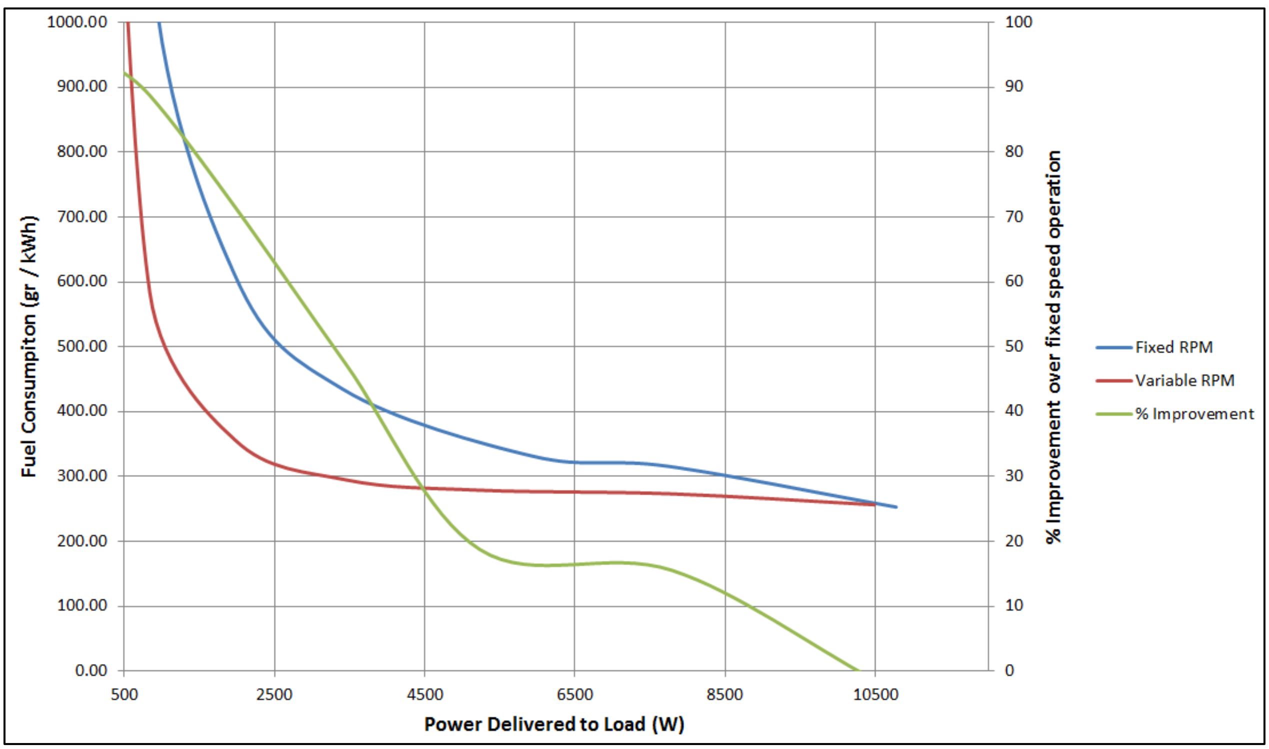


Figure 6 - Fuel consumption vs. power

D. Interpretation

As can be seen from the graph, the variable RPM mode is more efficient for the range measured. It should be kept in mind that the variable RPM was chosen arbitrarily. Therefore, this efficiency curve is not necessarily the optimal curve, but simply one curve chosen from the operating space of the system. To develop an optimal curve, a full efficiency map would need to be generated and an RPM would be chosen from a lookup table based on that map.

The green line represents the improvement of the variable RPM system over the fixed RPM system. The variable system is over 50% more efficient for the bottom third of the power range and shows significant efficiency improvement through most of the power range. We are looking forward to building a full efficiency map and developing an optimal curve for variable RPM performance.

Based on this technique it is possible to develop a very good estimate on how much efficiency improvement will be possible based on Brake Specific Fuel Consumption maps from engine manufactures. We will be dealing with a known quantity when selecting engines and stating efficiency improvements over existing generator sets.

Finally, optimal efficiency could always be achieved if the inverter was used in conjunction with energy storage. The beauty of the modular inverter system is that a battery can be added at any time with no change to the system other than firmware. Such a system would have tremendous benefits to marine and rural power systems.

5. IGBT Synchronization technique

A significant roadblock to fully modular inverter design is the problem of synchronizing multiple IGBT’s. Because the turn-on times are so fast, synchronization errors of more than 5 ns can cause inrush currents which eventually fail the semiconductor. During this quarter we successfully tested a method to discriminate nanosecond timing errors. During the next quarter we plan on incorporating this method into the PCB’s of our TRL seven design. Once the TRL-7 inverter is assembled we will be able to test this novel technique.

6. IP Dialogue

We began a dialogue with an intellectual property lawyer and are considering signing a retainer contract with him. The goal of the contract is the establishment of an IP model for our company. Once this model is in place it will guide our future IP decisions. We are hoping to have such a model in place during this quarter.

7. PCB Design

Another task which we started this quarter is the design of the TRL-7 UMIC. The TRL-7 will no longer include any prototype level features (other than the timing synchronization feature, which is not essential for most stack arrangements). One of the major design tasks for this project is the printed circuit board design. Prof. Steven Bitar from Worcester Polytechnic Institute (WPI) in Worcester, Mass. travelled to Kodiak for a week to work with us on the overall system architecture. He is now working with a group of senior electrical engineering students to design, build, and test the printed circuit boards for our design. WPI is looking forward to reproducing a complete version of the inverter in their power electronics lab for use in power measurement and motor control experiments. We are currently still in the design phase of our TRL-7 inverter and are working with the WPI group via weekly teleconference meetings.

Work for Next Quarter

1. Develop a full efficiency map of the proof-of-concept genset and deliver a complete data set on efficiency improvement.
2. Develop our motor efficiency testing algorithm and deliver motor efficiency results.
3. Develop FPGA code to deliver high speed efficiency data for inverter and motor.
4. Continue development of TRL-7 UMIC PCB’s and mechanical design.
5. Continue design of DE bus, including fuel efficiency measurement before conversion.
6. Select all components for 150kW (bus scale) genset.
7. Continue IP dialogues with a lawyer.